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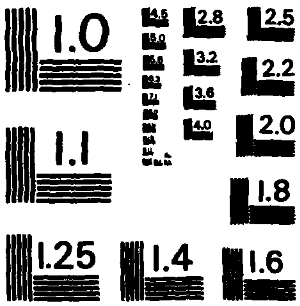

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East Hartford, Connecticut 06108

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Experimental and Analytical Study of the Effects of Free-Stream Turbulence on Turbulent Boundary Layers with Heat Transfer

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Final Scientific Report

Contract No. F49620-81-C-0053

REPORTED BY M. F. Blair

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APPROVED BY R P Dring

R. P. Dring

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

In an earlier AFOSR funded investigation, experimental research was conducted to determine the influence of free-stream turbulence on turbulent boundary layer heat transfer and mean profile development. The data obtained under this earlier contract indicated that both the skin friction and the heat transfer increased significantly with increased free-stream turbulence level. Under the present investigation, detailed boundary layer turbulence structural data and turbulent heat transfer data were obtained for experimental test conditions

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and profile locations selected from the earlier text matrix. Numerous measurements assured that the present test conditions (boundary layer development and free-stream turbulence distributions) duplicated those of the earlier AFOSR contract. The purposes for making these present detailed boundary layer turbulence measurements were: (1) to provide data to which current finite-difference boundary layer turbulence models could be compared, and (2) to generate a data base for the development of new analytical models for boundary layer heat transfer prediction. The results from the present program have shown that the distributions of both the turbulence kinetic energy and the turbulence structural coefficients were affected by increased levels of free-stream turbulence. Local profile measurements indicated that the effect of increased free-stream turbulence was to decrease the near-wall turbulent Prandtl number relative to values expected for low free-stream turbulence. Turbulent Prandtl numbers in the outer region of the boundary layer were slightly increased for higher free-stream turbulence. A turbulence dependent correlation for the measured distribution of turbulent Prandtl number is given.

With the completion of the experimental portion of this investigation, a theoretical effort was made to assess the capability of a finite difference boundary layer computer program, ABLE (Analysis of the Boundary Layer Equations) for predicting the effect of free-stream turbulence on momentum and thermal boundary layers. Comparisons with experimental data of mean flow velocity, mean flow temperature, Reynolds shear stress, turbulent heat transport, and turbulence kinetic energy were made in this investigation. In addition, the turbulent Prandtl number correlation deduced from the experimental measurements was used in the boundary layer analysis and its effect on surface heating evaluated. The results indicated that this boundary layer analysis, which uses a one equation eddy viscosity turbulence model, can provide adequate predictions of zero pressure gradient flows with high free-stream turbulence and wall heating.

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ABSTRACT

In an earlier AFOSR funded investigation, experimental research was conducted to determine the influence of free-stream turbulence on turbulent boundary layer heat transfer and mean profile development. The data obtained under this earlier contract indicated that both the skin friction and the heat transfer increased significantly with increased free-stream turbulence level. Under the present investigation, detailed boundary layer turbulence structural data and turbulent heat transfer data were obtained for experimental test conditions and profile locations selected from the earlier test matrix. Numerous measurements assured that the present test conditions (boundary layer development and free-stream turbulence distributions) duplicated those of the earlier AFOSR contract. The purposes for making these present detailed boundary layer turbulence measurements were: (1) to provide data to which current finite-difference boundary layer turbulence models could be compared, and (2) to generate a data base for the development of new analytical models for boundary layer heat transfer prediction. The results from the present program have shown that the distributions of both the turbulence kinetic energy and the turbulence structural coefficients were affected by increased levels of free-stream turbulence. Local profile measurements indicated that the effect of increased free-stream turbulence was to decrease the near-wall turbulent Prandtl number relative to values expected for low free-stream turbulence. Turbulent Prandtl numbers in the outer region of the boundary layer were slightly increased for higher free-stream turbulence. A turbulence dependent correlation for the measured distribution of turbulent Prandtl number is given.

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Experimental and Analytical Study of the Effects of Free-Stream Turbulence on Turbulent Boundary Layers with Heat Transfer

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Experimental and Analytical Effects of Free-Stream Turbulence on Turbulent Boundary Layers with Heat Transfer

STATEMENT OF WORK

The Contractor shall furnish scientific effort, together with all related services, facilities, supplies and materials, needed to conduct a study of the influence of free-stream turbulence in fully developed turbulent boundary layer flow. The following tasks will be included:

a. Using the UTRC Boundary Layer Wind Tunnel with test section adjusted to produce zero pressure gradient flow, various turbulence damping screens and generating grids will be employed to produce three test cases corresponding to ones examined under the previous period of AFOSR support. The free-stream velocity for these three test cases will be 100 fps and the test boundary layers will undergo natural transition to turbulent flow. The instrumentation utilized for these measurements will be the uniform flux heat transfer wall, single element and X-wire boundary layer hot-wire probes, 3 element X-wire boundary layer probes; conventional boundary layer pitot and thermocouple probes; and wall static taps. All hot wire data will be obtained using single or multiple channel constant temperature anemometers. Both analog signal processing and digital data reduction techniques will be employed. For reasons of accuracy, in particular, the resolution of the transverse fluctuating velocity component (w'), much of the turbulent velocity data will be obtained with isothermal flow (no wall heating). In the presence of wall heating, the specially designed 3-element hot-wire probe/data system will be employed for measurement of fluctuating temperature and turbulent Prandtl number distributions. As a check on the accuracy of the hot-wire profile data, measurements of the mean velocity and temperature distributions will be obtained with conventional pitot and thermocouple probes. Skin friction coefficients will be inferred from the mean velocity data. Where applicable the mean profile data will be reduced to the "universal" coordinates for turbulent boundary layers. A number of profile quantities will be measured by multiple techniques or methods. Mean velocity will be determined by means of pitot, single wire, X-wire and 3-element X-wire probes. Mean temperature will be measured by both thermocouple probes and the 3-element X-wire probes. Fluctuating velocity and Reynolds stress will be determined both with X-wire and 3-element X-wire techniques. For these cases of multiple measurements of the same profile quantities, comparisons of the results and analysis of the relative accuracies of each technique will be presented.

b. An analytical program will be conducted using a boundary layer analysis (ABLE) recently developed by the Contractor and generalized to accept the McDonald/Fish/Kreskovsky turbulence model and a variable turbulent Prandtl number. The measured data will be used as a basis to establish the functional form for the turbulent

Prandtl number distribution. The code will then be exercised and the results compared with the measured surface heat transfer data for the three test conditions of paragraph a.

INTRODUCTION

The search for improved gas turbine performance has led steadily in the direction of higher turbine inlet temperatures. The last twenty years have seen an increase in turbine inlet temperatures of roughly 1400°F but an increase in allowable blade metal temperature of only roughly 200°F. The difference between these two increases in temperature can be related directly to improved cooling technology. As an integral part of this advancing cooling technology, engine manufacturers are continually seeking improved techniques for calculating heat transfer coefficient distributions on gas turbine airfoils. As the level of cooling technology has been driven upward, and with it turbine inlet temperature, it is not surprising that the result is a design methodology which is extremely unforgiving of even small errors. The temptation is always present to overcool the airfoils but this is unacceptable due to the powerful negative impact of cooling air on the cycle and on turbine efficiency. It is this dilemma which has often led to extremely long and expensive developmental testing of advanced technology turbines.

Gas turbine thermal design systems are typically not based on fundamental fluid mechanics and heat transfer data and analysis alone but rather they are calibrated, or adjusted, to provide agreement with engine experience. Without the benefit of a first-principles understanding of the effects involved there is the likelihood that a designer will unknowingly either overcool the component or go beyond the range of validity of the design system calibration. There is, then, a clear requirement for the development of airfoil heat transfer distribution prediction procedures which are based on fundamental fluid mechanics and heat transfer data. The great emphasis placed on the development of accurate boundary layer calculation techniques over the past few years reflects the recognition of these needs.

One particularly important topic in the general context of turbine airfoil convective heat transfer is the influence of the free-stream turbulence on fully turbulent boundary layer development. It has, of course, long been recognized that increasing the free-stream turbulence level can cause a forward shift of the laminar to turbulent transition region. This particular phenomenon, the reduction of the boundary layer transition Reynolds number with increased free-stream turbulence level, is well documented in the open literature for zero pressure gradient flows and can be adequately predicted with currently available boundary layer prediction schemes. In addition, a number of investigators have studied the effects of free-stream turbulence level on turbulent boundary layer growth, profile structure, skin friction distribution and heat transfer. The consensus of these studies, is that free-stream turbulence has a very large and important influence on both the heat transfer and the boundary layer characteristics. As an example, it has been shown in a recently completed AFOSR funded contract at UTRC that a free-stream turbulence intensity of 5 percent produces an increase in Stanton number of approximately 15 percent over the value expected for a low turbulence freestream. While a number of existing boundary layer analysis procedures (including the UTRC ABLE code) account reasonably well for the influence of free-stream turbulence on mean velocity profile development and skin friction, no currently available analysis satisfactorily predicts the observed increased heat transfer rates.

The present program was designed to provide detailed boundary layer turbulence and turbulent heat flux distribution data for a range of free-stream turbulence levels. As part of this program these experimental data were employed to evaluate the analytical turbulence models currently incorporated in the UTRC ABLE code. It is anticipated that in the future these experimental data will be used by both UTRC and other workers in the field of boundary layer computation for development of new analytical turbulence models.

The contract effort consisted of acquiring, documenting and analyzing experimental flat wall boundary layer mean and fluctuating profile data to determine the influence of free-stream turbulence on fully turbulent boundary layer flows. For fully turbulent, zero pressure gradient flows, the following profile data were obtained for a range of free-stream turbulence intensities; boundary layer mean and fluctuating velocities and temperatures, turbulent shear stresses, and turbulent Prandtl numbers. In addition, in order to improve the ability of the UTRC boundary layer deck to predict the effects of free-stream turbulence on heat transfer rates, a turbulent Prandtl number distribution model was incorporated into the UTRC boundary layer code. Calculations were carried out employing the measured turbulent Prandtl number distributions and comparisons made between the predicted and measured heat transfer distributions.

STATUS OF THE RESEARCH EFFORT

The present program was designed to examine, both experimentally and analytically, the effect of the free-stream turbulence on the heat transfer through turbulent boundary layers. The experimental test conditions for the present program were intended to reproduce cases for which numerous other experimental data had been obtained under an earlier AFOSR contract. Measurements of multi-component free-stream turbulence intensities, test surface Stanton number distributions, transition Reynolds numbers and boundary layer integral thicknesses were in excellent agreement with the respective quantities of the earlier contract. It has been concluded that these present measurements can be viewed as additional data for the same test conditions as were previously studied. A number of comparisons were made between low free-stream turbulence boundary layer turbulence data obtained in the present study and similar results from other investigations. These comparisons showed excellent agreement indicating that the present boundary layer turbulence data are of high quality. A report describing the details of the work performed under this contract, UTRC R82-915634-2, "The Effects of Free-Stream Turbulence Structure and Heat Transfer in Zero Pressure Gradient Boundary Layers" has been prepared as an addendum to this Final Scientific Report. This detailed technical report contains the following: (1) details of the turbulence data acquisition and analysis techniques employed, (2) mean velocity and temperature boundary layer profiles for all experimental test conditions, (3) multi-component boundary layer turbulence and fluctuating temperature distributions for all experimental test conditions, (4) an analysis of the experimental results and (5) comparisons of the present experimental results with predictions of the UTRC Finite-Difference Boundary Layer Deck.

The conclusions reached from the experimental measurements were as follows:

1. The present data indicate a progressive increase of boundary layer turbulence kinetic energy with increasing free-stream turbulence. Increased levels of turbulence kinetic energy were measured across the entire thickness of the boundary layer. These results are in agreement with data from other independent studies.

2. Both the u' and w' components of turbulence increased progressively with increasing free-stream turbulence level. The u' component increased more than the w' component. The vertical component (v'), however, was essentially constant and independent of free-stream turbulence level for the inner half of the boundary layer.

3. The ratio of shear stress to turbulence kinetic energy decreased across the entire boundary layer with increasing free-stream turbulence level. The decrease was most extreme over the outer 60 percent of the boundary layer.

4. The effects of free-stream turbulence level on the ratios of the direct stress components to the turbulence kinetic energy were to a) increase $\overline{u'u'}/q^2$, b) decrease $\overline{v'v'}/q^2$ and c) leave $\overline{w'w'}/q^2$ nearly constant.

5. Reynolds stress distribution measurements indicated that at high levels of free-stream turbulence the turbulent shear stresses extend beyond the mean velocity boundary layer. The present data and results from other sources indicate an increase in turbulent shear at the boundary layer edge directly proportional to the free- ·eam turbulence level. Flatness factor measurements indicated th as the free-stream turbulence level was increased the "border" l een the fluid in the boundary layer and the free-stream fluid bec less distinct.

6. Measurements of the boundary layer turbulent Prandtl number distribution for the case of the low free-stream turbulence were in good agreement with a model suggested by Rotta. The present data indicate that as the free-stream turbulence level was increased, the near-wall Pr_t decreased while Pr_t over the outer region of the boundary layer slightly increased. A correlation, Pr_t (y/δ, Te), which fit the observed data reasonably well was suggested.

The experimental data were used to assess the capability of a boundary-layer computer program, ABLE (Analysis of the Boundary Layer Equations) for predicting the effect of free-stream turbulence on momentum and thermal boundary layers. In addition the turbulent Prandtl number formulation deduced from the experimental measurements was used in the boundary layer analysis and its effect on surface heating was determined. The following conclusions were reached from the theoretical portion of this investigation:

1. The modeling of free-stream turbulence in the one equation turbulence model of McDonald and Kreskovsky captures the correct shape and level of the turbulence kinetic energy.

2. For increased levels of free-stream turbulence, the Reynolds shear stress and turbulent heat flux determined from the turbulence model is significantly smaller than that observed experimentally in the wake region of the turbulent boundary layer. This discrepancy could be due to the eddy viscosity concept used in McDonald and Kreskovsky's model and further investigation of turbulence models is needed.

3. Analytical calculations using either Rotta's turbulent Prandtl number correlation or the correlation of the present investigation predicted Reynolds analogy factors ($2S_t/C_f$) that are in reasonable agreement with experimental measurements and accurately predict the increase in surface heat transfer due to increased free-stream turbulence.

LIST OF WRITTEN PUBLICATIONS

The following papers were presented at conferences and/or published in technical journals. Reprints of these papers will be sent to AFOSR when they are printed by ASME.

1. Title - Development of a Large-Scale Wind Tunnel for the Simulation of Turbomachinery Airfoil Boundary Layers

   Authors - Blair, M. F., Bailey, D. A. and Schlinker, R. H.

   Conference, Journal - Presented to 1981 ASME Gas Turbine Conference, Houston, TX, March 1981 -- Paper No. 81-GT-6, published in ASME Journal of Engineering for Power, Vol. 103, October 1981, pp. 678-687.

2. Title - Influence of Free-Stream Turbulence on Boundary Layer Transition in Favorable Pressure Gradients

   Author - Blair, M. F.

   Conference, Journal - Presented to 1982 ASME Gas Turbine Conference, London, England, April 1982 -- Paper No. 82-GT-4, published in ASME Journal of Engineerinf for Power, Vol. 104, October 1982, pp. 743-750.

3. Title - Influence of Free-Stream Turbulence on Turbulent Boundary Layer Heat Transfer and Mean Profile Development, Part I - Experimental Data, Part II - Analysis of Results

   Author - Blair, M. F.

   Journal - ASME Journal of Heat Transfer - to appear in February 1983 issue.

The following papers are currently being prepared for submission to conferences and journals. Copies of these papers will be sent to AFOSR simultaneously with their submission for publication. Likely title, authors and journals are as follows:

1. Title - Hot Wire Measurements of Velocity and Temperature Fluctuations in a Turbulent Boundary Layer

   Authors - Blair, M. F. and Bennett, J. C.

   Journal - ASME Journal of Heat Transfer

2. Title - Turbulent Heat Transport Through a Turbulent Boundary Layer With High Free-Stream Turbulence

   Author - Blair, M. F.

   Journal - ASME Journal of Heat Transfer

LIST OF PROFESSIONAL PERSONNEL ASSOCIATED WITH THE RESEARCH EFFORT

Blair, Michael F. - Senior Research Engineer, Gas Turbine Technology Group, Gas Dynamics and Thermophysics Laboratory - Principal Investigator

Edwards, David E. - Research Engineer, Computational Fluid Mechanics Research Group, Gas Dynamics and Thermophysics Laboratory

Dring, Robert P. - Manager, Gas Turbine Technology Group, Gas Dynamics and Thermophysics Laboratory

Carter, James E. - Manager, Computational Fluid Mechanics Research Group, Gas Dynamics and Thermophysics Laboratory

Werle, Michael J. - Manager of Gas Dynamics and Thermophysics Laboratory

INTERACTIONS

a. Spoken Papers - no spoken papers were delivered on this research.

b. Consultive and Advisory Functions - Discussions have been held with Professors Peter Bradshaw and David Gosman of Imperial College, London, regarding the subject matter of this contract. A number of useful suggestions concerning interpretation of the experimental data have resulted from these conversations.

LIST OF NEW DISCOVERIES OR PATENTS

No specific new discoveries or patents have resulted from any work conducted under this contract.

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